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Breakdown of the quantum Hall effect in InAs/AlSb quantum wells due to counterflowing edge channels

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We investigated magnetotransport in the two-dimensional electron gas (2DEG) present in InAs/AlSb quantum wells. The filling factor N_g underneath a gate electrode was reduced relative to the bulk filling factor N_b. For $N_g<N_b$ the resistance at the minima of the Shubnikov–de Haas oscillations failed to vanish, and the corresponding plateaus in the Hall resistance deviated from their expected quantized values $R_{xy}=h/(e^2N_g)$. The results are explained by the presence of anomalous edge channels at the 2DEG boundaries, which flow in opposite direction compared to the regular ones. They result from the band bending due to the combination of Fermi level pinning at the exposed InAs surface and the electrostatic potential generated by the gate electrode. This picture is supported by a comparison between the measured resistances and the resistances calculated with an edge channel model.

The quantum Hall effect[1] (QHE) can be observed in a two-dimensional electron gas (2DEG) subjected to a high perpendicular magnetic field B, provided that the electron mobility μ satisfies the condition $\mu B \gg 1$, and the temperature obeys the condition $kT \ll \hbar\omega_c, g\mu_B B$, with $\hbar\omega_c$ the Landau level spacing, and $g\mu_B B$ the Zeeman splitting. At those magnetic fields where the Fermi level E_F in the interior of the 2DEG is located in between the Nth and $(N+1)$th (spin-resolved) Landau level, the Hall resistance shows a quantized plateau at a value $R_{xy}=h/(e^2N)$. Simultaneously the corresponding longitudinal resistances R_{xx} vanish.

These observations can be explained with the edge channel picture of the quantum Hall effect.[2–6] The quantization of R_{xy} results from the one-dimensional nature of the edge channels, each contributing e^2/h to the Hall conductance. The vanishing of R_{xx} is due to the absence of current carrying states which connect the upper and lower edges of the 2DEG when E_F is located in between two Landau levels. The resulting absence of back scattering[6] makes both the upper and lower edges of the 2DEG become equipotentials.

Two mechanisms are known to lead to a breakdown of the above description for the QHE [we restrict ourselves to the linear transport regime, i.e., where all voltages V obey $eV \ll \hbar\omega_c$ (Ref. 7)]. When parallel conducting paths are present, for instance, in the form of additional 2D electron or hole subbands,[8,9] R_{xx} is prevented from vanishing, and at the same time the quantization of R_{xy} is destroyed.

A second mechanism is due to nonequilibrium occupation of edge channels.[10–13] It was shown that current and voltage probes which couple selectively to the edge channels can cause deviations from the regular QHE. In an extreme case the quantization of R_{xy} can even be determined completely by the filling factor in the probes, unrelated to the filling factor in the 2DEG.[13] It should be noted however that these nonequilibrium effects are usually restricted to length scales of the order of several μm or smaller, depending on the 2DEG mobility.[14] Also, these nonequilibrium effects can only be observed when the filling factor in the probes is reduced below the filling factor in the bulk 2DEG.

All experiments performed in the QHE regime so far have in common that the edge channels present at a particular boundary all carry current in the same direction, which is given by the electron drift velocity $\mathbf{v}_D=\mathbf{E}\times\mathbf{B}$, with $\mathbf{E}$ the electric field at the boundary. This boundary can be the physical edge of the 2DEG, formed, for instance, by mesa etching, or it can be the boundary between two regions with a different electron density n, created with gate electrodes.

We will study a quantum Hall system where edge channels at specific 2DEG boundaries can flow in *both* directions. We will study how these counterflowing edge channels lead to a breakdown of the QHE, giving rise to a finite resistance at the Shubnikov–de Haas (SdH) minima and a deviation from exact quantization in R_{xy}.

Our system consists of a 15-nm-thick InAs quantum well, confined in between (predominantly) AlSb barrier layers.[15] The total thickness of the top barrier layer is 40 nm. Metal contacts 1 to 10 are deposited on top of the InAs layer, after local removal of the top AlSb barrier layer [see Fig. 1(a)]. The Hall bar is then defined by chemical mesa etching, in which the top barrier layer outside the Hall bar region is removed first, followed by the removal of the underlying InAs layer. Finally, the center part (within the dashed line) of the Hall bar is covered by a Ti/Au gate electrode.

The measurements are performed at $T=4.2$ K, with an excitation current I small enough to prevent electron heating. Contacts 1 and 2 are used as current source and drain, respectively. SdH measurements show that at $V_g=0$ V a (single) 2DEG is present, with an electron density $n(V_g=0)=1.15\times10^{12}/\mathrm{cm}^2$, and a mobility $\mu=1.1\times10^5$ cm^2/V s. The 2DEG is fully depleted at a gate voltage $V_{gD}=-1.65$ V. A second 2D subband is occupied for gate voltages $V_g>+1.0$ V.

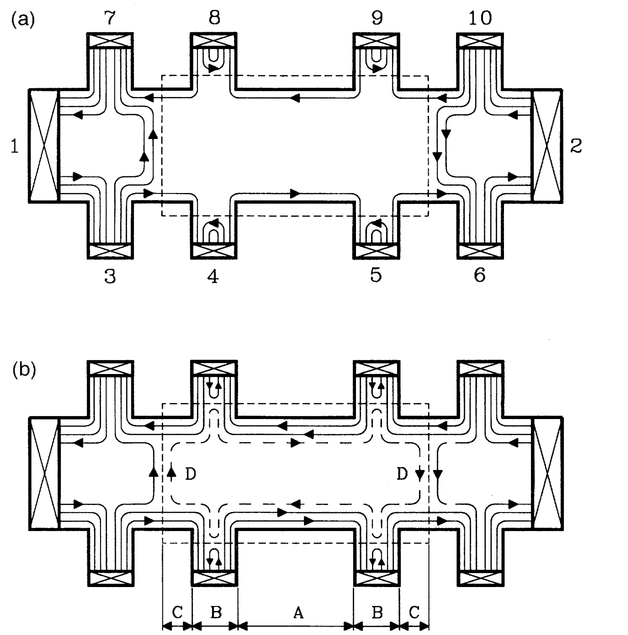

FIG. 1. (a) Regular edge channel configuration, illustrated for the case of $N_b=3$ and $N_g=1$. The dashed line indicates the area covered with a gate electrode. (b) Anomalous edge channel configuration showing the presence of regular (solid lines) and anomalous (dashed lines) edge channels at the 2DEG boundary. The lengths of the different sections of the 2DEG boundary are A, 420 μm; B, 20 μm; C, 170 μm; and D, 500 μm.

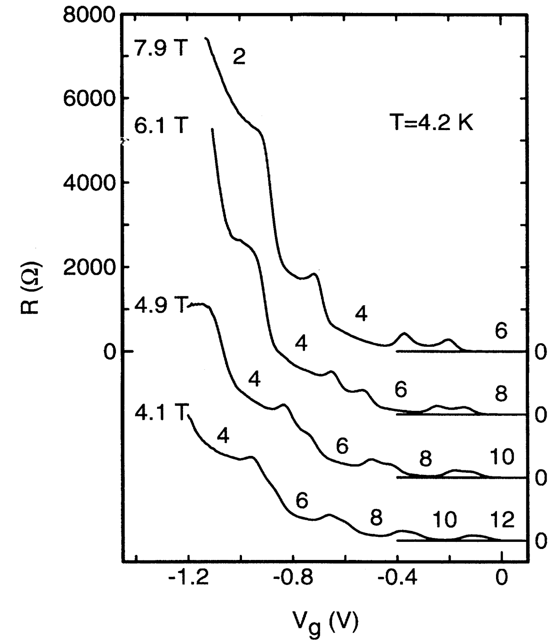

FIG. 2. Anomalous magnetoresistance $R_{4,5}$ measured as a function of gate voltage for bulk filling factors N_b =6, 8, 10, and 12. The filling factors N_g indicate the gate voltage intervals where the conventional SdH resistance should be zero. The curves are offset for clarity.

We focus on the magnetotransport in the regime where the filling factor N_g underneath the gated region of the Hall bar is reduced compared to the filling factor N_b of the ungated region.[16] For this situation the conventional edge channel picture is shown in Fig. 1(a), illustrating N_b edge channels flowing along the boundary of the ungated region, and N_g along the boundary of the gated region. At the boundary between both regions N_b-N_g channels are present, as a result of the electrostatic potential step induced by the gate.

Transport through the interior of the 2DEG is prohibited when both N_g and N_b are integer. The application of the Landauer-Büttiker formalism[6] then yields the following resistances: $R_{3,4}(=V_{3,4}/I)=0$, $R_{4,5}=0$, and $R_{5,9}=h/(e^2N_g)$. Figure 2 shows the measured $R_{4,5}$ as a function of V_g for several values of B, corresponding to $N_b=12$, 10, 8, and 6, respectively. For $V_g<-0.3$ V the SdH minima fail to approach zero resistance at integer filling factors N_g. The deviations become more pronounced with decreasing V_g and/or increasing B. A similar behavior is observed in the SdH minima of $R_{3,4}$, whereas the Hall plateaus observed in $R_{5,9}$ have a value lower than the expected quantized values $R_{5,9}=h/(e^2N_g)$.

The above findings are at odds with the conventional edge channel picture shown in Fig. 1(a). As noted already, according to this picture the absence of bulk transport implies $R_{3,4}=R_{4,5}=0$. We conjecture that the observed anomalies arise from the presence of additional edge channels at the boundaries of 2DEG underneath the gate, which carry current in opposite direction [see Fig. 1(b)]. The origin of these counterflowing edge channels may be explained with Fig. 3(a), which shows a cross section of the electrostatic potential in the gated region, both with and without a (negative) gate voltage bias. At the Hall bar boundary the InAs layer is terminated. For an exposed InAs surface the Fermi level is expected to be pinned above the conduction band edge E_c. The exact pinning position E_p was found to depend on the prior chemical treatment of the InAs.[17]

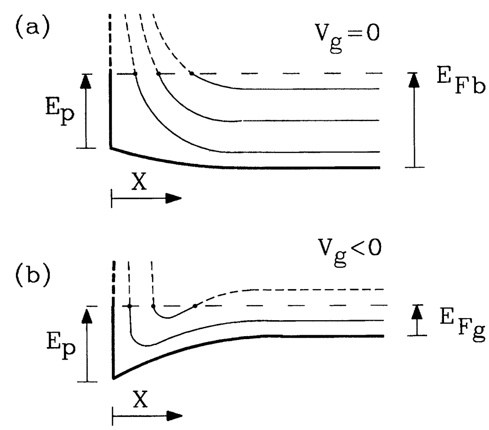

FIG. 3. Electrostatic potential (solid line) and Landau level (LL) dispersion as a function of the distance X from the 2DEG boundary, illustrated in the absence (a) and presence (b) of a negative gate voltage bias V_g. Edge channels are formed where the LL's intersect the Fermi energy. In (a) only regular edge channels are present, whereas (b) shows both regular and anomalous edge channels.

Due to this pinning the actual boundary of the 2DEG is formed by the physical boundary of the InAs layer. This is in contrast with the boundary of the 2DEG present, e.g., in GaAs/$Al_xGa_{1-x}As$ heterojunctions, where the boundary is due to the electrostatic depletion profile. From the onset of the anomalous behavior in Fig. 2 at $V_{g0} \approx -0.3$ V we estimate that the pinning level E_p is slightly less than the bulk Fermi energy E_{Fb} away from the boundaries [see Fig. 3(a)]. This result seems consistent with the results of Nguyen *et al.*,[17] who observed that the electron density in a 15-nm InAs quantum well located close to the surface is reduced to $n \approx 0.7 \times 10^{12}/\mathrm{cm}^2$, when the exposed surface layer consists of InAs. Note however that these results have been obtained on a planar layer geometry, whereas in our case the pinning occurs at the exposed edges of the InAs layer.

The potential profile of Fig. 3(a) implies that at $V_g = 0$ V only regular edge channels exist. Figure 3(b) shows that the application of a negative V_g results in an electric field, with an opposite sign and therefore induces an additional set of N_c counterflowing edge channels, whereas the number of regular edge channels is now given by $N_g + N_c$.

Transport in a similar geometry has been discussed theoretically by Barnes, Johnson, and Kirzenow.[18] They studied Anderson localization in a disordered waveguide with different numbers of modes propagating in opposite directions.

With the above picture we expect that N_c should increase linearly with the gate voltage, according to

$$N_c(V_g, B) = \frac{2E_{Fb}}{\hbar \omega_c} \frac{(V_g - V_{g0})}{V_{gD}}, \tag{1}$$

where $2E_{Fb}/\hbar \omega_c = N_g(V_g = 0, B)$ indicates the number of occupied Landau levels at $V_g = 0$ V. Two assumptions underlie Eq. (1): First, we assume that the pinning level E_p does not change when the electric field at the boundary is increased by applying a negative gate bias. Second, we assume that confinement effects due to the formation of a triangular potential well are not important.[19]

To test the above hypothesis, we calculated the resistances with two edge channel models, which include (back) scattering between edge channels. In particular, the strength of the scattering between the regular and anomalous edge channels is of crucial importance for the magnitude of the measured anomalies. For example, it is easily shown that strong scattering between the anomalous and regular edge channels will restore the conventional quantum Hall effect.

The following assumptions are made for the models.

(a) All edge channels flowing in the same direction along a particular boundary are assumed to be in equilibrium [there is one exception, to be specified in (c)]. The justification is that, due to the smaller spatial separation, the scattering rate between edge channels flowing in the same direction is usually much larger than the (back) scattering rate between channels flowing in opposite directions.

(b) The (back) scattering rate from the electrons out of one of the N_c anomalous channels into the $N_c + N_g$ regular channels in each of the four sections labeled C [see Fig. 1(b)] is described by a reflection probability $R^C_{a \to r}$. The corresponding transmission probability is therefore given by $T^C_{a \to a} = 1 - R^C_{a \to r}$. Detailed balance[6] requires that the corresponding quantities for transmission through, or reflection out of, the regular channels are given by $R^C_{r \to a} = R^C_{a \to r} N_c/(N_c + N_g)$ and $T^C_{r \to r} = 1 - R^C_{r \to a}$. The corresponding transmission and reflection probabilities in the two sections labeled A can be obtained by the appropriate scaling of the above quantities, taking into account the different lengths of sections A and C.[20]

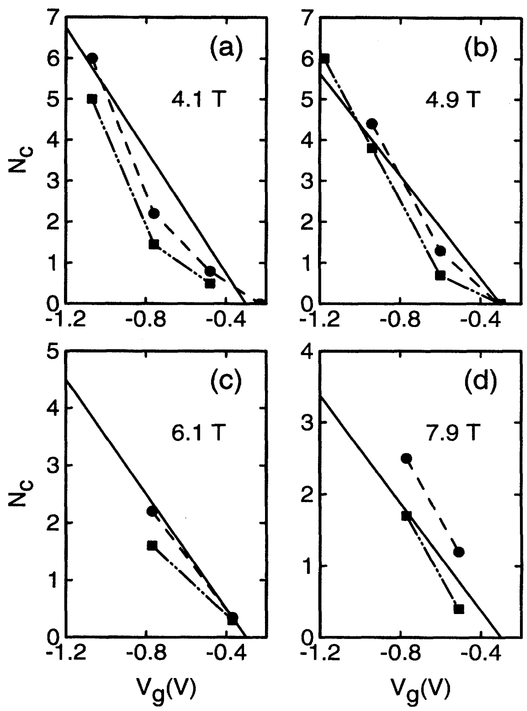

FIG. 4. Comparison between the theoretical number of anoma- edge channels N_c obtained from Eq. (1) (solid lines) and the ber obtained from the experimental data with models I (squares) and II (dots).

(c) In sections B and D regular and anomalous edge channels flow along the boundary of the gate electrode in the same direction. Given the relative long length of D (500 μm), we assume that the edge channels reach complete equilibrium along the two sections D. However, due to their shorter lengths, the situation along sections B is less clear. We therefore take two extreme cases: in model I we assume complete equilibration along sections B, in model II we assume that scattering between both sets of edge channels is absent.

(d) Finally, we do not discriminate between scattering processes which conserve electron spin, and those which involve spin-flip. Scattering between edge channels with opposite spin orientation was found to be suppressed, in particular in materials with weak spin-orbit interaction, such as Si.[21] However, as shown below, the need to discriminate between both scattering processes does not arise in our case.

(e) As usual in edge channel models with macroscopic contacts, we assume that the Ohmic contacts 1 to 10 are ideal.[6]

As input for the two models we used the experimental ratios $R_{3,4}/R_{4,10}$ and $R_{4,5}/R_{4,10}$, obtained for several integer values of N_g, at the four B values indicated in Fig. 2. The models then yield the values of N_c and the transmission probabilities which reproduce the measured data. The obtained values for N_c are shown in Fig. 4, together with the theoretical dependence, given by Eq. (1). Only those points are given, where the models gave physically acceptable solutions, (with $0 \leq T^C_{a\to a}, T^A_{a\to a} \leq 1$).

The agreement with the theoretical lines clearly supports the explanation in terms of anomalous edge channels, as given in Eq. (1). As can be see in Fig. 4, both models I and II give good agreement with Eq. (1), indicating that the results do not depend significantly on the assumptions made in (c). The obtained values for the transmission probabilities vary in the range $0.4 \leq T^C_{a\to a} \leq 0.65$ and $0.2 \leq T^A_{a\to a} \leq 0.35$, respectively. This indicates that the typical length scales over which equilibration between anomalous and regular edge channels occurs is in excess of 200 μm.

No physically acceptable solutions could be found with either model for $V_g < -0.8$ V in Figs. 4(c) and 4(d). The failure of both models to describe the data is directly related to fact that in this regime the measured resistance $R_{4,10}$ exceeds the value $R_{4,10} = h/(e^2 N_g)$, which is the maximum theoretical value which can be obtained with either model I or II. The reason for this discrepancy is yet unknown.

In summary we have identified a mechanism for the breakdown of the quantum Hall effect, which we showed to be due to the presence of anomalous counterflowing edge channels.

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